COMBINED METHOD FOR DIE COMPENSATION IN SHEET METAL FORMING

Agus Dwi Anggono

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For my beloved wife and family

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<div align="right">Agus Dwi Anggono, Parit Raja</div>

Abstract

Sheet metal forming is one of the prominent methods to convert blank sheet material into a product. In sheet metal forming, proper allowance of its tools must be given to the elastic recovery, due to the nature of elastic property which is called springback. When stamped sheet components are removed from the forming tools, the internal stresses will rest, and a new equilibrium state will be reached. As a result, the final shape of the drawn part will deviate from the shape imposed by the forming tool. Therefore, it is very important that springback be accurately predicted and compensated. In the industry, this is a costly and time consuming process of product shaping and redesigning the tools manually. The goal of this research is to develop a compensation procedure that can perform this optimization process, using the combination of Displacement Adjustment (DA) and Spring Forward (SF) methods. Both are based on an iterative procedure. The method is needed for guiding die design to compensate for springback in a backward direction and then to compensate springback in a forward direction. This new approach is then called Combined Method for Die Compensation (CMDC). The testing of CMDC has been conducted in 2D model of U-bending and 3D shape of S-rail model adopted from Numisheet 2008. The result shows that CMDC is able to reduce error in every cycle of the total five cycles. The result of reduction in shape deviation is 66% to 73% for the 2D model compensation, and for the 3D model, 55% reduction in shape deviation can be reached. The CMDC method can be further implemented and integrated in a commercial FEM software to assist the optimization process to improve the precision of stamping products.

Abstrak

Pembentukkan kepingan logam merupakan satu kaedah yang lazim digunapakai untuk mengubah kepingan bahan asal kepada produk. Dalam pembentukkan kepingan logam, secukupnya pada mata alat perlu diberikan untuk pemulihan elastik, ini kerana sifatnya yang dinamakan pembidasan. Diakhir proses mengecop kepingan kompenan, dimana mata alat pembentuk dikeluarkan, tekanan dalaman akan berubah dan mencapai satu tahap keseimbangan yang baru. Hasilnya, bentuk bahagian yang dicop akan berbeza daripada bentuk yang ditekan oleh mata alat. Oleh kerana itu, meramal pembidasan dengan tepat menjadi sangat penting dan dengan itu sifat semulajadi ini dapat diimbangi. Dalam industri kini, proses pembentukan produk dan merekabentuk semula mata alat secara manual memerlukan kos dan masa yang tinggi. Matlamat kajian ini adalah untuk membangunkan satu prosedur pengimbangan secara optimum, iaitu menggunakan gabungan kaedah Displacement Adjustment (DA) dan Spring Forward (SF). Kedua-dua kaedah ini berdasarkan prosedur berlelar. Kaedah ini diperlukan untuk mengawal reka bentuk die bagi mengimbangi pembidasan dalam arah ke belakang dan mengimbangi semula dalam arah ke hadapan. Kaedah baru ini dinamakan Combined Method for Die Compensation (CMDC). Ujian CMDC telah dijalankan mengunakan model ringkas 2D iaitu lenturan-U dan model 3D berbentuk S-rail yang telah diubah suai dari Numisheet 2008. CMDC ini dapat mengurangkan ralat pada setiap kitaran. Hasil pengurangan dalam sisihan bentuk adalah 66% kepada 73% bagi pampasan model 2D, dan untuk model 3D, pengurangan 55% dalam sisihan bentuk boleh dicapai. Kaedah CMDC ini boleh dikembangkan lagi dan boleh disepadukan dalam perisian FEM komersial untuk membantu proses pengoptimuman untuk meningkatkan ketepatan produk pengecopan.

Contents

ix

List of Figures

xi

List of Tables

List of Appendices

List of Symbols

Δy Shape error in y direction

$\vec{C}$ Compensated surface geometry

$\vec{R}$ Reference geometry

$\vec{S}$ Geometry after springback

$\overrightarrow{X^{i+1}}_{tool}$ New tool shape

$\overrightarrow{X^{i}}_{tool}$ Initial tool

$\Re^3$ Deformed surface

ρ Radius of curvature

σ_θ^p Plastic stress

σ_f Uni-axial flow stress

θ Bend angle

ε Tolerance of geometry error

ε_θ^{wh} Plastic strain

a Compensation factor

E Young's modulus

i^{th} Number of iteration

l Sheet length

lm Length of the fiber at mid plane

lo Sheet initial length

M Moment per unit width

n Number of point

N_{IP} Number of through-thickness Integration Points

R Bend radius

T Tension

t Sheet thickness

v Poisson's ratio

BHF   Blank Holder Force

CMDC   Combined Method for Die Compensation

DA   Diplacement Adjustment

FEM   Finite Element Method

IP   Integration Point

K B   Karafillis and Boyce

SF   Spring Forward

SMF   Sheet Metal Forming

Chapter 1

Introduction

Sheet metal forming (SMF) processes are shaping operations performed on metal sheets, strips, and coils. The surface area to the volume ratio of the starting metal is high. This ratio is a useful means to distinguish bulk deformation from sheet metal processes. Press working is the term often applied to sheet metal operation because the machines used to perform these operations are pressed. SMF process, consisting of stamping, forming, bending, stretching, trimming, and springback, used to convert sheet metal into a new part shape for a large variety of useful products (Groover, 2007). Sheet metals can be aluminum, nickel alloys, steel alloys, copper, brass, and titanium. SMF has become one of the most important manufacturing processes in industry, particularly in the automotive and steel industries (Lin & Kuo, 2008).

The most widely used SMF process is bending. Bending is the process by which a straight length is transformed to a curved length. The bending of sheet metal is called sheet bending. During the bending, the inner layers are subjected to compressive strain, and the outer fibers are subjected to tensile strain (Marciniak *et al.*, 2002). In between, there are layers, which have zero strains. The layers of zero strains in the plane of bending are called neutral axis. Its location is more towards the inner radius, as illustrated in Figure 1.1.

When the tool is removed at the end of the deformation operation, elastic energy remains in the part, causing it to recover partially to its original shape (GmbH, 1998). This elastic recovery is called springback, defined as the increase
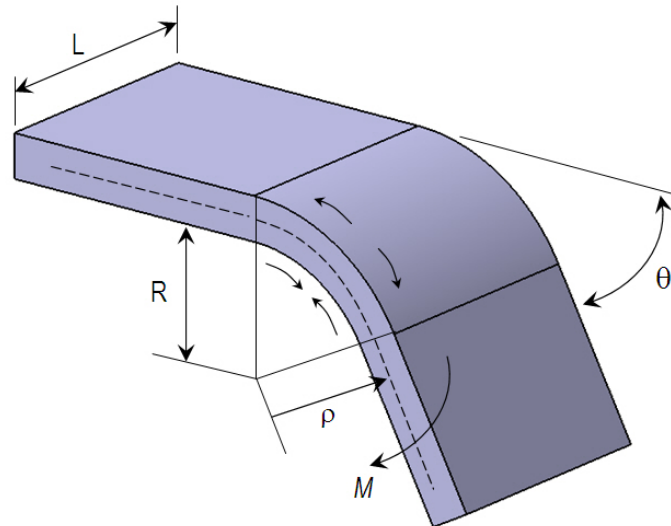
Figure 1.1: Sheet bending along a line

in included angle of the bent part relative to an included angle of the forming tool after it is removed. A springback occurs in all formed or bent-up parts on release of forming pressure and withdrawal of the punch (Hosford & Caddel, 2007). The springback illustration of pure bending is shown in Figure 1.2.

Since a springback always occurs in metals where the elastic property is present, then accommodating the springback rather than eliminating it (introduced by Karafillis & Boyce (1992b)) has become a new alternative. The conventional design of die surface based on the target formed shape is no longer appropriate. Instead, the die surface design should be optimised so that the formed shape after a springback will fall at the target shape. This approach is then called the die compensation for accommodating a springback. The early springback reduction by using die compensation was introduced by Ayres (1984), which had reduced a sidewall curl springback successfully compensated in high-strength steel rails. Webb & Hardt (1991) have applied a transfer function in sheet metal forming, while Karafillis & Boyce (1992a) have proposed a method to compensate springback by reversing the internal stress.

The springback compensation has then become an important design phase when the precision in product dimension is a major concern in sheet metal forming. In the past, the springback compensation was done manually by doing extensive measurements on a prototype or even production tools, and altering tool geometry by hand, which is a time consuming and costly-prohibitive process (Kobayashi *et al.*, 1989). In many cases, a number of iterations are needed during the compensation, which increases the cost of tool development. With
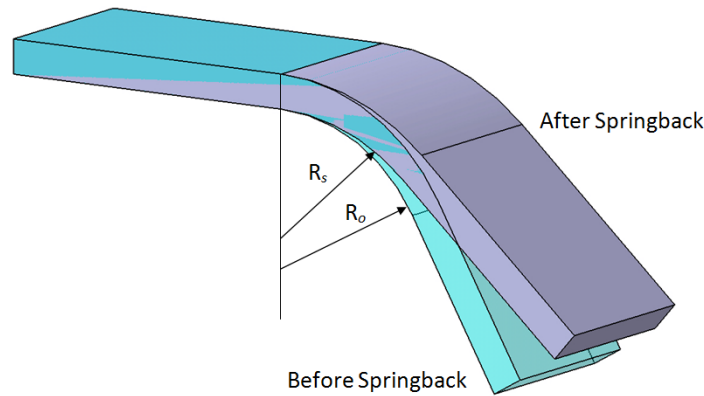
Figure 1.2: Springback occur in pure sheet bending

complex part shapes and new materials, it is difficult or even impossible to rely on such experience to estimate shape deviations and compensate the die surfaces (Tschaetsch, 2005).

Finite Element Methods (FEM) have been developed and used for sheet forming simulations since the 1970s, when continuum mechanics for problems involving large displacement and large strains became well established (Valberg, 2010). Modern finite element codes for SMF simulation have shown to be able to produce excellent results regarding the forming ability prediction as reported by Cho *et al.* (2003) in the investigation of springback characteristics, Bonte *et al.* (2004) in solving the optimization problem of metal forming process, and Andersson (2005) in the numerical analysis of springbacks in front side member. There are several commercial engineering codes which can be used for sheet forming simulation. Among them are ABAQUS Implicit/Explicit, Pam-Stamp, Ls-Dyna3D, HyperForm and AutoForm. These codes have been very common and frequently used for the benchmark sections of NUMISHEET conference series since NUMISHEET1993 (NUMISHEET1993, 1993).

In terms of the accurate simulation of a springback, there are still gaps where researchers are doing more investigations to improve the accuracy. The recently published report is from Gosling *et al.* (2011) that tries to speed up the compensation process and Wagoner *et al.* (2013) which has reported the advanced issue in springback compensation related to constitutive model, material properties, and thickness integration of stress.

The role of the springback simulation is critical and very important in the design stage of die surfaces. The accuracy of the predicted formed part, after the tools are removed, does not only depend on the springback analysis itself, but also

on the accuracy of forming processes. This has been identified by Panthi *et al.* (2010) in regard to the springback metal bending, and Marretta *et al.* (2010) for a specific optimal approach.

1.1 Background of Study

A numerical simulation with a finite element method has become a powerful tool in preventing the unwanted effects of sheet metal technological processing (Laurent *et al.*, 2010) including springback prediction, compensation and optimization(Meinders *et al.*, 2008). One of the most important problems in sheet metal forming is the compensation of a springback (Li *et al.*, 2002). In many cases the shape deviation of the sprung back part and the desired product is so large that the springback compensation is needed to obtain the desired product. That problem then becomes very crucial when the requirement of the shape accuracy is high. Many efforts have been done to eliminate the it by several researchers, the accuracy in springback measurement by Cardena *et al.* (2002), the modeling, screening, and solving of optimization problems in metal forming processes by Bonte *et al.* (2004), and Demirci *et al.* (2008). Therefore, the reduction of springbacks, while also avoiding excessive strain, is important to the success of a sheet metal-forming process.

The quantity of springback can be reduced by imparting the stretching in plastic area during its forming, however this can lead to tearing failure (Di Lorenzo *et al.*, 2009). Most approaches to control them focus on mechanical methods for increasing sheet tension during sheet bending. Sunseri *et al.* (1996) used an active binder force control, and Liu *et al.* (2002) studied the variable blank holder force.

Although it is impossible to prevent springbacks, they can be minimized by using several approaches, for instance, reinforcing part by smaller radii or additional folding, and raising the stretching deformation of the sheet (Roll *et al.*, 2005). Even so, there are still many cases where its deviation exceeds the given tolerance. Where the minimized one is still so large that the subsequent assembly operation is seriously influenced, the additional geometric modification of the tool surface, the so-called springback compensation, has to be introduced in order to reduce the shape deviation between the drawn part and the desired product.

Nowadays, springbacks can be predicted accurately (Cho *et al.*, 2003),

Cleveland & Ghosh (2002) predict them affected by inelastic effects, Geng & Wagoner (2002) have improved the springback accuracy by using the role of plastic anisotropy, and Dongjuan *et al.* (2006) have studied on non-linear combined hardening rule and Barlat's 89 yield function to predict them, but there still remains the problem of how to use such results to appear in a suitable die design to produce a target part shape (Rochowski, 2001). That is, the springback predictions allow a forward analysis of forming and springback, while a backward analysis is needed to work from these results back toward an optimized die design. It is the second step of springback compensation that is addressed in the current work.

Two common methods of springback compensation are explained in the literature, the Displacement Adjustment (DA) method (Gan & Wagoner, 2004) and the Spring Forward (SF) proposed by Karafillis & Boyce (1992a) and its improved version (Karafillis & Boyce, 1992b) which is called as Karafillis & Boyce (K&B) method. The DA method is a strictly geometrical method, to move the surface nodes defining the die surface in the direction opposite to the springback error. The displacement vectors at each node are used to adjust the trial die design until the target part shape is achieved. The K&B method has a more physical approach, based on the internal stresses that cause springback and computing the constraint forces to maintain equilibrium following form (Karafillis & Boyce, 1992a).

In the review of the literature the DA method is deemed faster than the SF method in convergence finding. This method minimizes a springback error rapidly, while that one does not reduce an error to an acceptable value. However, DA iterations may oscillate while SF iterations show steadily decreasing errors (Gan & Wagoner, 2004). The convergence speed of the DA method also depends on materials, processes and geometrical parameters (Papeleux & Ponthot, 2002; Parente *et al.*, 2006). The SF method is sensitive to the position of fixation points due to high compressive stresses in the blank, and due to buckling effects, the calculation of the compensated geometry is impossible in most cases (Gan & Wagoner, 2004; Lingbeek, 2005).

The DA and the SF methods are utilized to compensate the die shape because this step is done before the production process. The equipment used to apply them are a computer and a finite element software which are cheaper compared to the cost of a trial and error. The DA approach is very simple due to the algorithm based on the process. Therefore, there is no artificial error

introduced in the calculation compared with the SF approach (Lingbeek, 2005). The SF approach is based on the assumption that the sign change of residual stress correspondingly results in spring forward (SF). The combination of both methods will provide a compensation strategy with their advantages.

1.2 Problem Statement

The recent research in springback compensation has examined several methods relating to the product accuracy. The strategies of the compensation by adjusting the tooling shape are DA and SF methods. The DA method is a numerical solution based on a springback phenomenon. The compensation is conducted by translating the springback shape to the opposite direction; therefore the DA is easily understood and implemented. The problem of the DA method is that it can not converge in the sidewall area (Gan & Wagoner, 2004).

The SF method is a compensation strategy by employing the residual stress to the original shape. Due to the involvement of stress distribution, this method is fully based on a finite element method. The advantage of the SF is it could converge in any direction and able to compensate in selected shapes. However, SF is slow to decrease errors and choices of boundary condition in finite elements (Gan & Wagoner, 2004; Cheng *et al.*, 2007). Thus research in this area will provide an important link or an amalgamation between the DA and the SF methods to adjust the tooling shape.

1.3 Objective

This research embarks on the following objectives:

1. To use Autoform FE to investigate the accuracy of springback predictions at variations of blank holder force (BHF); number of elements; material properties; and drawbead models.

2. To validate the Autoform springback results.

3. To use Autoform FE to investigate the die compensation method at variation of compensation types; and compensation factors.

4. To combine the DA and the SF methods as a die compensation method.

1.4 Scope of Study

The scopes of the research are:

1. To accommodate springback error in sheet metal forming using Displacement Adjustment (DA) method.

2. To accommodate springback error in sheet metal forming by using Spring Forward (SF) method.

3. The DA and the SF methods will be combined to accommodate springbacks in sheet metal forming, and the proposed method will be called Combined Method for Die Compensation (CMDC).

1.5 Expected Results

At the end of the research, a new strategy with a general capability in die compensations can be combined with a finite element effectively. The new approach of die shape compensation can be applied to any type of surface models both 2D and 3D.

1.6 Thesis Outline

This research is based on using finite a element method to develop a springback-compensated die shape in sheet metal forming. The thesis outline is as follows:

Chapter 1 outline the motivation behind this research along with the objectives of the research, scopes of study and expected research results.

Chapter 2 presents a comprehensive overview of sheet metal forming, reviews of the sensitivity springback analysis including the effects of element sizes and types, the effects of the time step and integration point, the effects of material model and the effects of drawbead model and blank holder force. It reviews the

types of springback error compensations, displacement adjustments and spring forward method. This chapter is a literature review of the available theory and knowledge used for developing of springback compensation algorithm.

Chapter 3 gives a description of the research plan and methodology, die compensation of simple 2D model and advance 3D model by applying the previous methods of DA, SF, and the proposed Combined Method for Die Compensation.

Chapter 4 contains results and discussions which provide a description and investigations of the accuracy springback predictions and die compensations. The accuracy of springbacks is influenced by material models, number of elements or mesh size, integration points, and blank holder force. The investigations are implemented to the U-bending, Arc-bending and S-rail models. The springback results are considered for die compensation for all tester components. The recommendation for the accurate springback will be presented in the end of the springback section. This chapter also presents a proposed method to compensate the die surface by using the methodology described in Chapter 3 as called Combined Method for Die Compensation. The compensation procedure test is starts from the simple 2D model, the U-bending and S-rail 3D model. The comparison result of the Combined Method for Die Compensation and Autoform is presented in this chapter.

The summarized contributions of this work and the expected benefits of this work applied in sheet metal forming are described in Chapter 5.

Chapter 2

Literature Review

Researchers have been studying the phenomenon of springback for nearly four decades. The discussion of it is firstly published by Akamatsu *et al.* (1966), and since then it has become an ongoing problem when the accuracy of forming products is required. Since this problem in sheet metal forming is unavoidable, many researchers have been trying to minimize it.

There are many ways to handle springback. They are basically grouped into two: one is *minimizing it* by controlling parameters contributing to the springback; the other one is *accommodating it*. The main difference of the two methods is in the design paradigm of the die surface. The first group considers die surface is based on the target formed part (Li *et al.*, 2002; Cafuta *et al.*, 2012; Kitayama *et al.*, 2013), whereas the second group optimizes the die surface to compensate it, pioneered by Karafillis & Boyce (1992b) and the latest publications from some researchers (Yang & Ruan, 2012; Chang, 2013; Han *et al.*, 2013). The work in this thesis belongs to the second group which is accommodating springback.

This chapter provides a comprehensive review related springback theories, literature on springback error and compensation methods in the manufacturing process of sheet metal forming. At the end of this chapter, an alternate direction in the die compensation approach is presented.
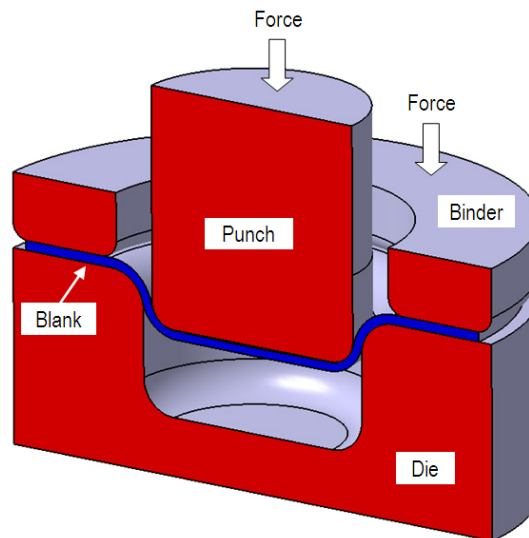
Figure 2.1: Parts of sheet metal forming

2.1 Introduction to Sheet Metal Forming

Metal forming is a process of plastically deforming of raw material to become a product. It can be generally classified into two classes: bulk metal forming and sheet metal forming (Marciniak *et al.*, 2002). In the bulk metal forming processes, usually the work-piece has a high volume to surface area ratio. In the sheet metal forming processes, the work-piece sheet has a low volume to surface area ratio. Some examples of the SMF processes are deep drawing, stretch forming, bending, and spinning (GmbH, 1998).

The principle of deep drawing is schematically represented in Figure 2.1. The drawn blank sheets are produced by a rolling operation. It is one of the fundamental forms used in metalworking and it can be cut and bent into a variety of shapes. Thicknesses can vary significantly which have high ratio of surface area to thickness (Groover, 2007). In the sheet metal forming process, final product thickness is kept from the excessive reduction to avoid thinning, wrinkling and cracking, as reported by researchers, Sarkar *et al.* (2002); Marretta *et al.* (2010) have decided a failure criterion in sheet metal forming from the thinning, and Di Lorenzo *et al.* (2009) have concerned in controlling of thinning and springback.

In the SMF, the quality of its final product is determined by the process parameters, shape and materials of blank, and the tool design (Tschaetsch, 2005). This is important to carefully consider all the parameters prior to die manufacturing to produce the accurate products. Types of defects which commonly occurs
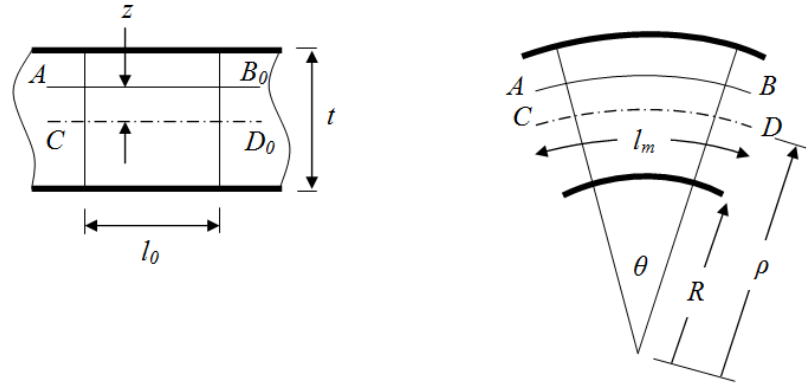
Figure 2.2: Longitudinal layers in bending and tension (Marciniak *et al.*, 2002).

in sheet metal forming are wrinkling (GmbH, 1998), thinning (Marretta *et al.*, 2010), cracking, and necking (Bonte *et al.*, 2004). In addition to these defects, there is always dimension deviation caused by springback as well (Cimolin *et al.*, 2008). Because springback always occurs, it is the most common problem in sheet metal forming and needs to be minimized or to be compensated (Gan & Wagoner, 2004; Mole *et al.*, 2014).

2.2 Springback Analysis in Pure Bending

Analytical solutions for springback are first derived for simple model in two-dimensional cases, such as stretch bending, plane strain bending, drawing and plane strain cyclic bending (Marciniak *et al.*, 2002). As shown in Figure 1.1, a bend angle is θ, and a moment per unit width M, and a tension T are applied. The T is applied in the middle surface of the sheet.

The bending radius could be more than three or four times of the thickness of the sheet. The plane normal section in the sheet will remain plane and normal and converge on the center of curvature as illustrated in Figure 2.2. A line CD_0 in the middle surface of the plate may change its length to CD during bending. The original length l_0 of the line CD_0 becomes

$$l_m = \rho\theta \tag{2.1}$$

which is the arc length of the line CD.

After bending to an angle θ with a radius of curvature ρ, the initial length l_o will deform to a length l, situated at distance z above the mid-surface. The

radius of curvature is defined as $\rho = R + t/2$ where t is the thickness of material and R is inner radius. The segment length l can be expressed as a function of the length of the fiber at the mid-surface $l_m = \rho\vartheta$, the radius of curvature and the distance z:

$$l = (\rho + z)\theta = l_m \left(1 + \frac{z}{\rho}\right) \tag{2.2}$$

The circumferential true strain is given by:

$$\varepsilon_\theta = ln(l/lo) = ln\left[\frac{l_m}{l_o}\left(1 + \frac{z}{\rho}\right)\right] \tag{2.3}$$

that can be split in the true strain in the mid-plane:

$$\varepsilon_a = ln(\frac{l_m}{l_o}) \tag{2.4}$$

and the additional bending true strain:

$$\varepsilon_b = ln\left(1 + \frac{z}{\rho}\right) \tag{2.5}$$

In the case of a large R, the difference between the true strain and the engineering strain is negligible, however, the engineering strain is easier to handle. The membrane and bending engineering strains can be written as:

$$\varepsilon_m = \triangle l_m/l_o \tag{2.6}$$

$$\varepsilon_b = \frac{z}{\rho} \tag{2.7}$$

The membrane strain has a value of:

$$\varepsilon_m = \frac{a}{\rho} \tag{2.8}$$

where a is the position of a neutral line, as seen in Figure 2.3. The total engineering circumferential strain becomes:

$$\varepsilon_\theta = \frac{z + a}{\rho} \tag{2.9}$$

The assumption of the material behavior in this model is isotropic. In a plane strain situation, in the case of the von Mises yield condition the main

principal stress can be found from (Marciniak *et al.*, 2002):

$$\sigma_1 = \frac{2}{\sqrt{3}}\sigma_f = S_o \tag{2.10}$$

where σ_f is the uni-axial flow stress and S_o is the plane strain flow stress.

Generally, a metallic material will behave following elastic-plastic with strain-hardening pattern. In the elastic range, the stress in the circumferential direction is found from Hooke's law for plane strain:

$$\sigma_\theta = \frac{E}{1-v^2}\varepsilon_\theta = E'\varepsilon_\theta \tag{2.11}$$

where E is the Young's modulus and v is the Poisson's ratio. The plastic strain-hardening behavior is approximated by a power law:

$$\sigma_\theta = C'\left(\varepsilon_o + \varepsilon_\theta^p\right)^n \tag{2.12}$$

C' and n hardening parameters and ε_o being a pre-strain which can be calculated from the initial condition:

$$\sigma_{f(0)} = C\varepsilon_\theta^n \tag{2.13}$$

weher $\sigma_{f(0)}$ is the initial uni-axial yield stress and C is the material strength coefficient in the uni-axial case.

The relation between the plane strain and uni-axial value of this parameter can then be approximated by:

$$C' \approx C\left(\frac{2}{\sqrt{3}}\right)^{n+1} \tag{2.14}$$

2.2.1 Loading Phase

The unit width of a continuous sheet in which a cylindrical bent region of radius of curvature ρ is flanked by a flat sheet, as shown in Figure 1.1. A bend angle is θ, and a moment per unit width M, and a tension T are applied. The position of yield points in regions where the material is in tension or compression can be seen in Figure 2.3.

The coordinates of yield points in tension and compression regions are:

$$z_1 = -a + b_1 \tag{2.15}$$

$$z_2 = -a - b_2 \tag{2.16}$$

Considering Eq. (2.15) and Eq. (2.16) then substituting into Eq. (2.9) gives the bending yield strains in tension region

$$\varepsilon_{\theta t}^y = \frac{z_1 + a}{\rho} = \frac{b_1}{\rho} \tag{2.17}$$

and in compression region

$$\varepsilon_{\theta c}^y = \frac{z_2 + a}{\rho} = \frac{b_2}{\rho} \tag{2.18}$$

The variables b_1 and b_2 define the boundaries of elastic region and can be found by using Hooke's low:

$$b_1 = b_2 = \rho\varepsilon_{\theta t}^y = \frac{\rho}{E'}S_o \tag{2.19}$$

where E' is defined by Eq. (2.11) and S_o is the initial plane strain flow stress, Eq. (2.10).

Since the sum of the constant strain at yield (ε_θ^y) and the strain due to the material work-hardening (ε_θ^{wh}) is the total circumferential strain (ε_θ) in the region of plastic deformations.

$$\varepsilon_\theta = \varepsilon_\theta^y + \varepsilon_\theta^{wh} \tag{2.20}$$

The strain due to the material work-hardening in tension and compression regions can be written as:

$$\varepsilon_{\theta t}^{wh} = \varepsilon_{\theta t} - \varepsilon_{\theta t}^y = \frac{z + a}{\rho} - \frac{S_o}{E'} \tag{2.21}$$

$$\varepsilon_{\theta c}^{wh} = \varepsilon_{\theta c} - \varepsilon_{\theta c}^y = \frac{z + a}{\rho} + \frac{S_o}{E'} \tag{2.22}$$

From the Eq. (2.12), the circumferential stress in the plastic deformation region is determined. The plastic strain must be known, to calculate the stress. However, since the power law represents a non-linear hardening behavior, the plastic strain is not known beforehand. Therefore an approximation is made by equating the plastic strain to the strain due to work-hardening. The plastic strain $\varepsilon_\theta^p = \varepsilon_\theta - \varepsilon_\theta^e$ is smaller than the strain due to work-hardening $\varepsilon_\theta^{wh} = \varepsilon_\theta - \varepsilon_\theta^y$, and thus the circumferential stress is overestimated.

As a result, the circumferential stress in the plastic part of the material in tension region can be written as:

$$\sigma_{\theta t}^{p} = C' \left(\varepsilon_o + \frac{z+a}{\rho} - \frac{S_o}{E'} \right)^{n} \tag{2.23}$$

whereas in compression region

$$\sigma_{\theta c}^{p} = -C' \left(\varepsilon_o + \left| \frac{z+a}{\rho} - \frac{S_o}{E'} \right| \right)^{n} \tag{2.24}$$

The bending moments and the forces acting on the sheet per unit length can be found from:

$$T = \int_{-t/2}^{t/2} \sigma_\theta dz \tag{2.25}$$

$$M = \int_{-t/2}^{t/2} \sigma_\theta z \, dz \tag{2.26}$$

The tensile force can be split into three components:

$$T = T^e + T_T^p + T_C^p \tag{2.27}$$

where T^e is the force caused by the elastic stresses, T_T^p and T_C^p are the tensile and the compressive forces caused by the plastic stresses. The contribution of the elastic and the plastic stresses to the total tension will be:

$$T^e = \int_{z_2}^{z_1} E' \frac{z+a}{\rho} \, dz \tag{2.28}$$

$$T_T^p = \int_{z_1}^{t/2} C' \left(\varepsilon_o + \frac{z+a}{\rho} - \frac{S_o}{E'} \right)^{n} dz \tag{2.29}$$

$$T_C^p = -\int_{-t/2}^{z_2} C' \left(\varepsilon_o + \left| \frac{z+a}{\rho} - \frac{S_o}{E'} \right| \right)^{n} dz \tag{2.30}$$

The analytical solution of the Eq. (2.28) and Eq. (2.30) can be found in Appendix C.
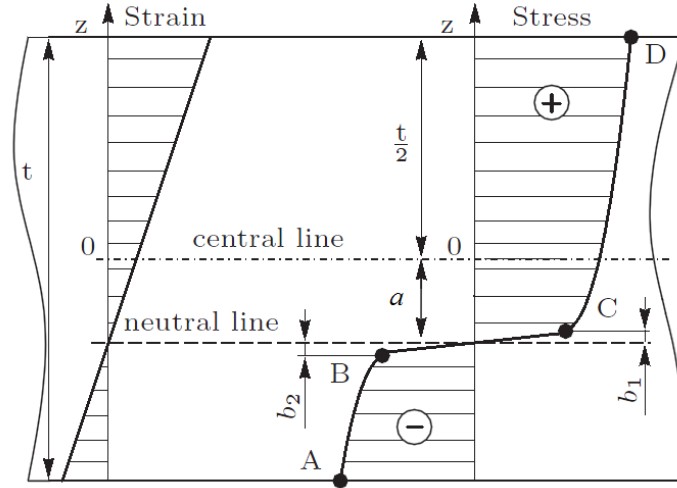
Figure 2.3: Equilibrium diagram of stress distribution (Marciniak *et al.*, 2002).

The total moment per unit width acting about the mid-plane is

$$M = M^e + M_T^p + M_C^p \tag{2.31}$$

where M^e is the elastic part, $M_T^p + M_C^p$ are the plastic part of the total bending moment in the region of tension and compression. The components can be found as follows:

$$M^e = \int_{z_2}^{z_1} E' \frac{z+a}{\rho} z \, dz \tag{2.32}$$

$$M_T^p = \int_{z_1}^{t/2} C' \left(\varepsilon_o + \frac{z+a}{\rho} - \frac{S_o}{E'} \right)^n z \, dz \tag{2.33}$$

$$M_C^p = - \int_{-t/2}^{z_2} C' \left(\varepsilon_o + \left| \frac{z+a}{\rho} - \frac{S_o}{E'} \right| \right)^n z \, dz \tag{2.34}$$

The complete solutions of Eq. (2.32) and Eq. (2.34) are presented in Appendix C.

2.2.2 Unloading Phase

After bending a sheet to a radius R, a moment M still remains in the material. When the tools are removed, the bending moment is released and the sheet will spring back to a new position to reach an equilibrium state. The stress magnitude is decreased and the amount of shape changes can be related to the applied bending moment.

The change in internal stresses due to elastic unloading reads:

$$\triangle \sigma_\theta = E' \triangle \varepsilon_\theta \tag{2.35}$$

where

$$\triangle \varepsilon_\theta = \frac{z}{\rho} - \frac{z}{\rho'} = \triangle \left(\frac{1}{\rho} \right) z \tag{2.36}$$

the term ρ' is the radius of curvature after unloading.

The change in internal stresses causes a change in a bending moment, $\triangle M$ as expressed by

$$\triangle M = \int\limits_{-t/2}^{t/2} \triangle \sigma_\theta z \, dz = \int\limits_{-t/2}^{t/2} E' \triangle \left(\frac{1}{\rho} \right) z^2 \, dz \tag{2.37}$$

$$\triangle M = \frac{E't^3}{12} \triangle \left(\frac{1}{\rho} \right) = \frac{t^3}{12} \frac{\triangle \sigma_\theta}{z} \tag{2.38}$$

Since the removal of external loads results in $\triangle M = -M$,

$$\frac{E't^3}{12} \triangle \left(\frac{1}{\rho} \right) = -M \tag{2.39}$$

thus, the change in the curvature is related to the applied bending moment,

$$\triangle \left(\frac{1}{\rho} \right) = -\frac{12M}{E't^3} \tag{2.40}$$

The bending angle is changed due to the change of curvature. It can be determined from the arc length l of the bend which remains constant after bending and during unloading, hence:

$$l = \theta \rho \implies \theta = \frac{l}{\rho} \tag{2.41}$$

The expression for the change of an angle $\triangle \theta$ can be obtained by differentiating the above equation to the curvature:

$$\frac{d\theta}{d \left(\frac{1}{\rho} \right)} = l = \rho \theta \implies d\theta = d \left(\frac{1}{\rho} \right) \rho \theta \tag{2.42}$$

$\triangle\theta$ can be calculated from:

$$\triangle\theta = \triangle\left(\frac{1}{\rho}\right)\rho\theta = -\frac{12M}{E't^3}\rho\theta \tag{2.43}$$

2.3 Reviews of Springback in Sheet Metal Forming

In every process of deep drawing or stamping, a springback phenomenon theoretically always exists that involves plastic deformations (Cleveland & Ghosh, 2002; Nanu & Brabie, 2011). Although it is generally negligible, there are many instances in which, because of the form and dimension of the piece or depending on the material and consequently causes bad parts to be produced.

A springback analysis is often an important part of a forming analysis because it determines the shape of the final, unloaded part. It can be considered as a dimensional deviation which happens during the removal of the load because of the primarily elastic recovery of the material.

Nowadays aluminum alloys and high strength steels are commonly used in automotive industries to reduce weight ratio (Das *et al.*, 2007) and the trend of aluminum consumption has grown steadily (Das & Yin, 2007). However, because of these materials higher ratios of yield strength to elastic modulus (Rees, 2006) that contribute to the springback, precise prediction and control of springback become essential. Springback becomes a crucial issue and a major quality concern in the stamping field (Banabic, 2010).

Finite element (FE) simulations are used extensively in sheet metal stamping industries (Valberg, 2010) in which the technology has contributed to a better understanding of sheet metal forming processes and in which the prediction capabilities have significantly reduced the time consuming, inexact and costly die tryouts (Parente *et al.*, 2006).

An accurate modeling of the sheet metal deformations including the springback prediction is one of the key factors in the efficient utilization of Finite Element Method (FEM) process simulation in industrial application. When the die tools are removed from the part and the springback occurs, the forming simulation will not be useful (Valberg, 2010). The accurate simulation should be further performed to see the final product shape after the constraint removal. The geometry defects such as thinning and wrinkling are contributed by metal

elastic behavior (Banu *et al.*, 2006; Cai *et al.*, 2008).

Springback is a complex phenomenon which is primarily governed by a stress state obtained at the end of a deformation. There are several types of springback in sheet metal forming, depending on the product geometry such as bending, membrane, twisting and combined bending and membrane (Wang, 2002). The types commonly observed in industrial practice are combined bending and membrane springback.

Controlling of springback in sheet metal forming requires that this phenomenon is well understood. Springback is the most significant factor that makes it difficult to achieve the required dimensional accuracy of stamped components. Designing a die with incorrect springback compensation can lead to significant difficulties in downstream operations such as poor fit-up during welding and distortion of sub-assemblies (Liu *et al.*, 2013). Springback can appear in a positive deformation on one side and a negative one on the other side compared with the target part (Weiher *et al.*, 2004).

More complex experiments and tests have been developed to obtain a better understanding of material behavior in realistic deformation regimes (Cardena *et al.*, 2002; Cheng *et al.*, 2007). Experimental investigations have shown that the springback phenomenon in sheet metals also involves small scale plasticity effects and is thus not fully elastic (Cleveland & Ghosh, 2002; Teodosiu, 2005).

During simulation, the springback prediction is conducted as the last step of the sheet forming simulation, consequently, any numerical errors delivered from the forming process will be accumulated and will influence the springback analysis (Xu *et al.*, 2004). Therefore, the accuracy of a springback simulation is not only related to the springback analysis itself but also strongly dependent on the accuracy of the forming processes.

The parameters that may contribute in springback simulation accuracy are element size, time step, integration point (Lin & Liu, 2000), material model (Dongjuan *et al.*, 2006), drawbead design (Bae *et al.*, 2008) and blank holder force (BHF) (Demirci *et al.*, 2008).
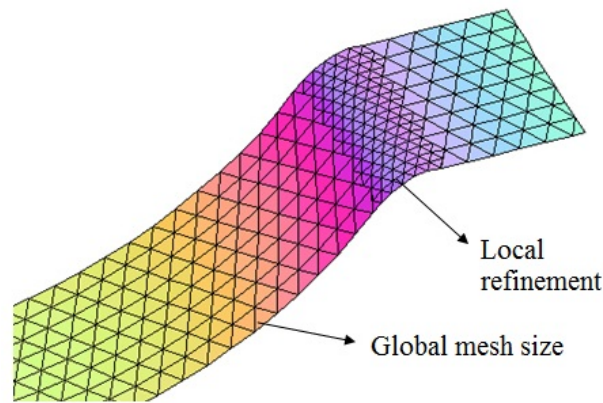
Figure 2.4: Smaller element in the bending region for accuracy improvement.

2.3.1 The Effect of The Element Size and Element Type

Linear shell elements with 3 or 4 nodes are widely used in numerical simulations of sheet metal forming due to cheaper cost (Kobayashi *et al.*, 1989; Polyblank *et al.*, 2014). Their accuracy has been well verified for the simulations in flat regions, in which the relative curvature (t/R) is smaller than $(1/6)$. However, the calculated error cannot be neglected in small bending/inverse bending regions $(t/R < 1/6)$ (Li & Wagoner, 1998) where the linear shape function is insufficient. To improve the accuracy of simulation in bending/inverse bending regions, a smaller element size is required as illustrated in Figure 2.4.

When the element size reaches 1/2~1/3 of relative bending radii, the magnitude of calculating springback is starting to be robust and no further improvement is introduced any more (Lin & Liu, 2000). It should be further understood that the further decrease of element size will not only notably increase the time consumption, but also increase the cost of contact treatment and matrix solution, which might inversely introduce additional error of springback simulation (Cho *et al.*, 2003).

Element type is also important for accurate results in a finite element analysis. The blank required to discretise depends on the geometry of the sheet part and the problem. The representative finite elements can be in 2D plane strain, solid, and shell elements (Bhavikatti, 2005). The element commonly used in sheet metal forming simulation is a shell element (Logan, 2007). A node in the shell element has five degrees of freedom: three translations towards the two tangent vectors and the normal vectors, and two rotations with the tangent vectors as the axis of rotation (Autoform, 2010). Another element wisely used is the element with six degrees of freedom per node. For a 6 DOF element node,

the degrees of freedom are the three translations and three rotations. Some of the widely used shell elements in practice are three-node flat facet and curved triangle; six-node triangle; four-node, eight-node and nine-node quadrilaterals (Bhavikatti, 2005). In all elements, all nodes are in the mid surface of the element.

The inclination of the shell cross section can be described in relation to the element surface with the use of the rotational degree of freedom and thus a transverse shear deformation in the element kinetics can be taken into account. Such a shear soft element formulation corresponds to the Reissner-Mindlin theory (Kobayashi *et al.*, 1989). The use of the shell element is mandatory, for the process of forming, bending, hydro forming and springback (Autoform, 2010).

Dynaform proposed the MSTEP module, the higher precise quadrilateral membrane element model and Discrete Kirchhoff Quadrilateral (DKQ) shell is employed (Gladman, 2013). Therefore, a fast iteration convergence in solving the group of equations can be obtained. In MSTEP, the computational speed is faster than the traditional algorithm.

2.3.2 The Effect of The Time Step and Integration Point

A time step can influence the description of strain and stress history and only applicable in an explicit method to calculate their response (Lee & Yang, 1998). The explicit method is initially utilized to analyze a contact based on the forming operation of a production stamping process. In implicit this is not relevant, the time step is a time tag to obtain a result, not related to calculation algorithm (Logan, 2007). An implicit solution is performed to simulate a springback that develops in a blank after the forming pressure has been removed.

A smaller time step will result in more accurate simulation results and more stable, however, the time consumption will be increased as well (Narkeeran & Michael, 1999). In the dynamic explicit method, the unbalanced force between the internal force and the external force is considered as a driving force acting on a mass. The explicit method is unsuitable for a springback simulation (Jung, 2002), because the springback which needs static solutions cannot be obtained rapidly in dynamic state (Noels *et al.*, 2004).

Springback is sensitive to process parameters and various materials (Xu *et al.*, 2004). FE simulation of springback adds numerical sensitivity in the form of element size, element type, (N_{IP}), tolerance, (Akamatsu *et al.*, 1966) and

Bauschinger effect (Uemori *et al.*, 1998). Larger N_{IP} can more accurately reproduce continuous stress distribution, and also the post forming bending moment, but at the expense of increased computation time, as reported by several researchers (Lin & Liu, 2000; Xu *et al.*, 2004).

Several subsequent reports in the literature including the ones find no differences in springback for 3–10 integration points (Andersson & Holmberg, 2002), 7 and 15 IP being adequate (Lin & Liu, 2000), marginal differences between 5 and 20 IP (Xu *et al.*, 2004). Some reports go further, with specific recommendations for small N_{IP}: 7 IP for minimizing sensitivity (Yao *et al.*, 2002), 9 IP for accuracy (Nguyen & Bapanapalli, 2009), and 7 IP for more accurate answers than 3, 5 or 11 (Xu *et al.*, 2004), however, although the varying number of integration point are specified but it is still an open issue in springback simulation. A default value for N_{IP} of 5 appears in shell elements for some commercial software: Abaqus (Abaqus, 2004) and Pam-Stamp (Sever *et al.*, 2012), whereas NIP of 9 is recommended for better accuracy in LS-Dyna (Nguyen & Bapanapalli, 2009). These references, imply that N_{IP} is not a critical numerical parameter in a springback simulation, at least for N_{IP} greater than about 5. Many papers that report springback predictions do not report N_{IP} at all (Gan & Wagoner, 2004; Cimolin *et al.*, 2008; Gosling *et al.*, 2011).

2.3.3 The Effect of Material Constitutive Model

Many metals have an approximately linear elastic behavior at low strain magnitudes and the stiffness of the material, known as the Young's or elastic modulus, is constant (Hosford & Caddel, 2007). At a higher stress and strain magnitudes, metals begin to have a nonlinear, inelastic behavior, which is referred to plasticity.

One of the key successes in numerical simulations of sheet metal forming is material modeling (Teodosiu, 2005). The hardening model is widely thought to have an obvious influence on a springback simulation (Geng & Wagoner, 2002). Figure 2.5 shows the comparison of calculated springback between isotropic hardening model and kinematic hardening model.

However, the improvement of calculated springback with kinematic hardening model is not guaranteed because of many factors affected its accuracy (Kobayashi *et al.*, 1989). Some examples with negative influence have been found as well during the investigation. The reason can be explained as follows. There
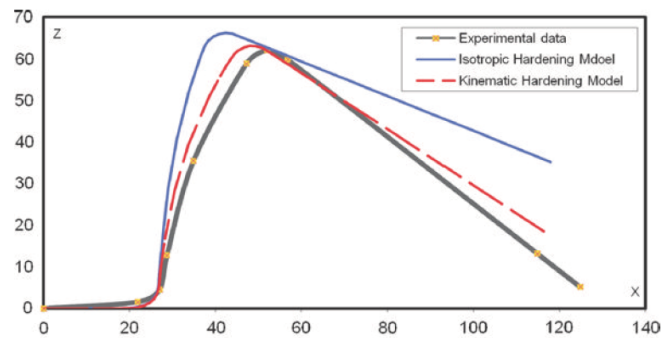
Figure 2.5: The comparison of calculated springback between isotropic and kinematic hardening model; from Xu *et al.* (2004)

are two main factors in the kinematic hardening model which may influence the final springback result; these are the transient softening of the hardening curve and the reduction of Young's modulus. While the factor of Young's modulus reduction will cause larger springback deformation, on the other hand, the factor of transient softening of the unloading hardening curve will inversely result in smaller springback deviation (Valberg, 2010). The final springback result is determined by the combined influence of the two factors.

In reality, the measurement of kinematic hardening parameters is not so easy (Rees, 2006). In many cases, the error of measurement is so large that even a springback simulation becomes worse. For an accurate springback simulation, well-measured experimental data related to kinematic hardening parameters are required (Autoform, 2010). The flow curve could be determined experimentally by a tensile test.

2.3.4 The Effect of The Drawbead Model and Blank Holder Force

Drawbeads are widely used in stamping processes which aim at controlling the material flow and improving the formability (Bae *et al.*, 2008). There are two types of drawbead models in numerical simulation, which are, namely, physical drawbead and equivalent drawbead model (GmbH, 1998). Physical drawbead is a real model in 3D type while the equivalent drawbead is a simple model such as line or spline which is defined as drawbead.

The physical drawbead model can simulate the real behavior of bending and inverse bending history (Bae *et al.*, 2008). However, it requires about 2.5~8 times more computation time than the equivalent drawbead model (Hora, 2008). Moreover, the radii of drawbeads are commonly so small that the application

limit of shell theory is often exceeded, which will introduce great challenges in numerical simulation of sheet metal forming.

Due to the above mentioned reasons, the equivalent drawbead model is widely used in numerical simulation (Smith *et al.*, 2005), and it has been verified to provide good accuracy in formability prediction (Hora, 2008). The springback analysis, however, is still in the discussion due to the neglection of bending and inverse bending history in the equivalent drawbead model. However, when the material passing a drawbead remains on the final part, the difference of bending or inverse bending history resulting from drawbead model cannot be neglected and the physical drawbead model is necessary (Smith *et al.*, 2008).

Many researchers have studied the effect of blank holder force (BHF) in the springback analysis (Hishida & Wagoner, 1993; Liu *et al.*, 2002; Demirci *et al.*, 2008). Liu (Liu *et al.*, 2002) has proposed a method to reduce springback using variable blank holder force (VBHF). VBHF is determined by the value of low blank holder force (BHF_L) and high blank holder force (BHF_S). The method has been applied in the forming process of U-bend model adopted from NU-MISHEET'93 successfully reduce springback error compared to the application of constant blank holder force (CBHF). However, a precision binder force control during forming is required, making this process sensitive to any variations in manufacturing conditions such a friction coefficient.

2.4 Reviews of The Springback Error Compensation

The industry of sheet metal forming relies on two groups of strategy to control springback, they are mechanical based reduction and geometrical based compensation (Wang, 2002). The first method is based on the optimization of the mechanics of sheet metal forming. For example, blank holder force (BHF), punch velocity and punch force. The study of blank holder force to control springback is reported by several researchers and the optimal BHF can minimize a springback error, Sunseri *et al.* (1996) has minimized springbacks by using active binder force control, Liu *et al.* (2002) has done it with the variable blank holder force as mentioned above, and Yoshihara *et al.* (2005) has studied the effect of blank holder force in deep drawing. Multiple steps of sheet metal forming is another example of mechanical method. This method is conducted by using several sets of tools with some additional mechanisms (Nguyen & Bapanapalli, 2009).

References

Abaqus (2004). *Abaqus/Standard User's Manual 6.5 (2004)*. Dassault Systemes.

Akamatsu, T., Yanagimoto, S., Aoki, I. & Hanai, S. (1966). Effect of mechanical properties of sheet steel on the springback of press-formed parts. *Eighth Biennial Congress and Conference of IDDR*, 11.

Andersson, A. (2005). Numerical and experimental evaluation of springback in a front side member. *Journal of Materials Processing Technology*, 169(3), pp. 352 – 356.

Andersson, A. & Holmberg, S. (2002). Simulation and verification of different parameters effect on springback results. *Proceedings of the 5th International Conference and Workshop on Numerical Simulation of 3D Sheet Forming Processes (NUMISHEET 2002)*, pp. 201–210.

Anggono, A., Siswanto, W. & Omar, B. (2011). Combined method of spring-forward and spring-back for die compensation acceleration. In: *Modeling, Simulation and Applied Optimization (ICMSAO), 2011 4th International Conference on*, pp. 1 –6.

Autoform (2010). *AutoForm plus R2 Documentation*. AutoForm engineering.

Ayres, R. (1984). Shapeset: A process to reduce sidewall curl springback in high-strength steel rails. *Journal of Applied Metalworking*, 3(2), pp. 127–134.

Bae, G.H., Huh, H. & Park, S.H. (2008). Simulation-based prediction model of draw-bead restraining force and normal force. *Proceedings of the 7th International Conference and Workshop on Numerical Simulation of 3D Sheet Metal Forming Processes*, pp. 443–448.

98

Banabic, D. (2007). *Advanced method in material forming.* Springer.

Banabic, D. (2010). *Sheet metal forming processes constitutive modelling and numerical simulation.* Springer.

Banu, M., Takamura, M., Hama, T., Naidim, O., Teodosiu, C. & Makinouchi, A. (2006). Simulation of springback and wrinkling in stamping of a dual phase steel rail-shaped part. *Journal of Materials Processing Technology*, 173(2), pp. 178 – 184.

Bhavikatti, S.S. (2005). *Finite element analysis.* New Age International Pablisher.

Bonte, M.H.A., van den Boogaard, A.H. & Veldman, E. (2004). Modelling, screening, and solving of optimisation problems: Application to industrial metal forming processes. *ESAFORM Conference on Material Forming*, 82, pp. 1695–1705.

Brabie, G., Costache, E. & Chirita, B. (2014). Reduction of the sheet thickness variation and its negative effects on the accuracy of mini drawn parts using different geometries of tool components. *Precision Engineering*, (0), pp. –.

Cafuta, G., Mole, N. & Å tok, B. (2012). An enhanced displacement adjustment method springback and thinning compensation. *Materials & Design*, 40(0), pp. 476 – 487.

Cai, Z.Y., Wang, S.H. & Li, M.Z. (2008). Numerical investigation of multi-point forming process for sheet metal: wrinkling, dimpling and springback. *The International Journal of Advanced Manufacturing Technology*, 37, pp. 927–936.

Cardena, W., Genga, L., Matlockb, D. & Wagonera, R. (2002). Measurement of springback. *International Journal of Mechanical Sciences*, 44, pp. 79–101.

Chang, K.H. (2013). Chapter 4 - sheet metal forming simulation. In: *Product Manufacturing and Cost Estimating Using Cad/Cae* (ed. K.H. Chang), The Computer Aided Engineering Design Series, Boston: Academic Press, ISBN 978-0-12-401745-0, pp. 133 – 190.

Chen, Z. & Dong, X. (2009). The {GTN} damage model based on hill'48 anisotropic yield criterion and its application in sheet metal forming. *Computational Materials Science*, 44(3), pp. 1013 – 1021.

Cheng, H.S., Cao, J. & Xia, Z.C. (2007). An accelerated springback compensation method. *International Journal of Mechanical Sciences*, 49(3), pp. 267 – 279.

Cho, J., Moon, S., Moon, Y. & Kang, S. (2003). Finite element investigation on spring-back characteristics in sheet metal u-bending process. *Journal of Materials Processing Technology*, 141(1), pp. 109 – 116.

Cimolin, F., Vadori, R. & Canuto, C. (2008). Springback compensation in deep drawing applications. *Springer Science+Business Media B.V.*, 48, pp. 101–113.

Cleveland, R.M. & Ghosh, A.K. (2002). Inelastic effects on springback in metals. *International Journal of Plasticity*, 18, pp. 769–785.

Das, S., Green, J. & Kaufman, J. (2007). The development of recycle-friendly automotive aluminum alloys. *JOM Journal of the Minerals, Metals and Materials Society*, 59, pp. 47–51, 10.1007/s11837-007-0140-2.

Das, S. & Yin, W. (2007). Trends in the global aluminum fabrication industry. *JOM Journal of the Minerals, Metals and Materials Society*, 59, pp. 83–87, 10.1007/s11837-007-0027-2.

Demirci, H.I., Esner, C. & Yasar, M. (2008). Effect of the blank holder force on drawing of aluminum alloy square cup: Theoretical and experimental investigation. *Journal of Materials Processing Technology*, 206(1-3), pp. 152 – 160.

Di Lorenzo, R., Ingarao, G., Micari, F. & Chinesta, F. (2009). A pareto optimal design approach for simultaneous control of thinning and springback in stamping processes. *International Journal of Material Forming*, 2, pp. 801–804, 10.1007/s12289-009-0485-x.

Dong, F., Du, L., Liu, X. & Xue, F. (2013). Optimization of chemical compositions in low-carbon al-killed enamel steel produced by ultra-fast continuous annealing. *Materials Characterization*, 84(0), pp. 81 – 87.

Dongjuan, Z., Zhenshan, C., Xueyu, R. & Yuqiang, L. (2006). Sheet springback prediction based on non-linear combined hardening rule and barlat 89's yielding function. In: *Computational computer science*.

Gan, W. & Wagoner, R.H. (2004). Die design method for sheet springback. *International Journal of Mechanical Sciences*, 46(7), pp. 1097 – 1113.

Geng, L. & Wagoner, R.H. (2002). Role of plastic anisotropy and its evolution on springback. *International Journal of Mechanical Sciences*, 44(1), pp. 123 – 148.

Gladman, B. (2013). *LS-DYNA Keyword User's Manual.* LIVERMORE SOFTWARE TECHNOLOGY CORPORATION (LSTC).

GmbH, S. (1998). *Metal forming handbook.* Springer, 1st edition.

Gosling, M., Kracker, H., Brosius, A., Kuhnt, S. & Tekkaya, A. (2011). Strategies for springback compensation regarding process robustness. *Production Engineering*, 5(1), pp. 49–57.

Green, D.E. (2005). Description of numisheet 2005 benchmark 3 stage-1: Channel draw with 75894–904.

Groover, M.P. (2007). *Fundamentals of Modern Manufacturing, Materials, Processes, and Systems.* John Wiley and Sons.

Han, F., hua Mo, J., wei Qi, H., fen Long, R., hui Cui, X. & wei Li, Z. (2013). Springback prediction for incremental sheet forming based on fem-psonn technology. *Transactions of Nonferrous Metals Society of China*, 23(4), pp. 1061 – 1071.

Hishida, Y. & Wagoner, R.H. (1993). Experimental analysis of blank holding force control in sheet forming. *Society of Automotive Engineers Technical Paper No. 930285.*

Hora, P. (2008). Numerical simulation of 3d sheet metal forming processes-verification of simulation with experiment. *Proceedings of the 7th International Conference and Workshop on Numerical Simulation of 3D Sheet Metal Forming Processes.*

Hosford, W.F. & Caddel, R.M. (2007). *Metal Forming Mechanics and Metallurgy.* Cambrige University Press.

Jung, D. (2002). Static-explicit finite element method and its application to draw-

bead process with spring-back. *Journal of Materials Processing Technology*, 128(13), pp. 292 – 301.

Karafillis, A.P. & Boyce, M.C. (1992a). Tooling design accommodating spring-back errors. *Journal of Material Process Technology*, 32, pp. 499–508.

Karafillis, A.P. & Boyce, M.C. (1992b). Tooling design in sheet metal forming using springback calculations. *International Journal Mechanical Science*, 34, pp. 113–131.

Karafillis, A.P. & Boyce, M.C. (1996). Tooling and binder design for sheet metal forming processes compensating springback error. *International Journal of Machine Tools and Manufacture*, 36(4), pp. 503 – 526.

Kergen, R. & Jodogne, P. (1992). Computerized control of the blankholder pressure on deep drawing presses. *Society of Automotive Engineers Technical Paper No. 920433*.

Kitayama, S., Huang, S. & Yamazaki, K. (2013). Optimization of variable blank holder force trajectory for springback reduction via sequential approximate optimization with radial basis function network. *Structural and Multidisciplinary Optimization*, 47(2), pp. 289–300.

Kobayashi, S., Oh, S.I. & Altan, T. (1989). *Metal forming and the finite-element method*. Oxford University Press.

Kubli, W., Krasovskyy, A. & Sester, M. (2008). Advanced modeling of reverse loading effects for sheet metal forming processes. *Proceedings of the 7th International Conference and Workshop on Numerical Simulation of 3D Sheet Metal Forming Processes*, pp. 479–484.

Laurent, H., Graze, R., Oliveira, M., Menezes, L., Manach, P. & Alves, J. (2010). Numerical study of springback using the split-ring test for an aa5754 aluminum alloy. *Finite Elements in Analysis and Design*, 46(9), pp. 751 – 759.

Lee, S. & Yang, D. (1998). An assessment of numerical parameters influencing springback in explicit finite element analysis of sheet metal forming process. *Journal of Materials Processing Technology*, 8081(0), pp. 60 – 67.

Li, K., Carden, W. & Wagoner, R.H. (2002). Simulation of springback. *International Journal of Mechanical Sciences*, 44, pp. 103–122.

Li, K. & Wagoner, R.H. (1998). Simulation of springback. in: Huetink j, baaijens fpt (eds) simulation of materials processing: Theory, methods and applications. *Proceedings of the 6th International Conference on NUMIFORM 1998, Enschede.*, pp. 21–31.

Lin, B.T. & Kuo, C.C. (2008). Application of an integrated cad/cae/cam system for stamping dies for automobiles. *The International Journal of Advanced Manufacturing Technology*, 35, pp. 1000–1013, 10.1007/s00170-006-0785-y.

Lin, Z. & Liu, G. (2000). Study on the effects of numerical parameters on the precision of springback prediction. *Proceedings of the 6th International LS DYNA User's Conference.*

Lingbeek, R. (2005). Springback compensation of industrial parts with the displacement adjustment and springforward methods: Milestone 1.

Liu, G., Lin, Z., Xu, W. & Bao, Y. (2002). Variable blankholder force in u-shaped part forming for eliminating springback error. *Journal of Materials Processing Technology*, 120, pp. 259–264.

Liu, K., Ma, N. & Liu, Q. (2013). Investigation on the application of hot forming in the automotive component design.

Logan, D.L. (2007). *A First Course in the Finite Element Method.* Thomson.

Marciniak, Z., Duncan, J.L. & Hu, S.J. (2002). *Mechanics of Sheet Metal Forming.* Butterworth-Heinemann.

Marretta, L., Ingarao, G. & Lorenzo, R.D. (2010). Design of sheet stamping operations to control springback and thinning: A multi-objective stochastic optimization approach. *International Journal of Mechanical Sciences*, 52(7), pp. 914 – 927.

Meinders, T., Burchitz, I., Bonte, M. & Lingbeek, R. (2008). Numerical product design: Springback prediction, compensation and optimization. *International Journal of Machine Tools and Manufacture*, 48(5), pp. 499 – 514, advances in Sheet Metal Forming Applications.

Mole, N., Cafuta, G. & Å tok, B. (2014). A 3d forming tool optimisation method considering springback and thinning compensation. *Journal of Materials Processing Technology*, 214(8), pp. 1673 – 1685.

Munier, M., Devin, J.M. & El-Mouatassim, M. (2004). New approach for spring-back compensation in die design application for high strength steel. *Revue de Métallurgie*, 101, pp. 607–613.

Nanu, N. & Brabie, G. (2011). Influence of material properties on the interaction between residual stress and springback in the case of in plane sheets forming. *Archives of Civil and Mechanical Engineering*, 11(4), pp. 979 – 991.

Narkeeran, N. & Michael, L. (1999). Predicting springback in sheet metal forming: An explicit to implicit sequential solution procedure. *Finite Element in Analysis and Design*, 33, pp. 29–42.

Nguyen, B.N. & Bapanapalli, S.K. (2009). Forming analysis of az31 magnesium alloy sheets by means of a multistep inverse approach. *Materials and Design*, 30(4), pp. 992 – 999.

Noels, L., Stainier, L. & Ponthot, J.P. (2004). Combined implicit/explicit time-integration algorithms for the numerical simulation of sheet metal forming. *Journal of Computational and Applied Mathematics*, 168(12), pp. 331 – 339, selected Papers from the Second International Conference on Advanced Computational Methods in Engineering (ACOMEN 2002).

NUMISHEET1993 (1993). 2nd international conference on numerical simulation of 3-d sheet metal forming processes. In: *Isehara, Japan, 31 August - 2 September 1993*.

NUMISHEET2008 (2008). 7th international conference and workshop on numerical simulation of 3d sheet metal forming processes. In: *Interlaken, Switzerland*.

Panthi, S., Ramakrishnan, N., Ahmed, M., Singh, S.S. & Goel, M. (2010). Finite element analysis of sheet metal bending process to predict the springback. *Materials and Design*, 31(2), pp. 657 – 662.

Papeleux, L. & Ponthot, J.P. (2002). Finite element simulation of springback

in sheet metal forming. *Journal of Materials Processing Technology*, 125-126(0), pp. 785 – 791.

Parente, M., Valente, R.F., Jorge, R.N., Cardoso, R. & de Sousa, R.A. (2006). Sheet metal forming simulation using eas solid-shell finite elements. *Finite Elements in Analysis and Design*, 42(13), pp. 1137 – 1149.

Polyblank, J.A., Allwood, J.M. & Duncan, S.R. (2014). Closed-loop control of product properties in metal forming: a review and prospectus. *Journal of Materials Processing Technology*, (0), pp. –.

Rees, D.W.A. (2006). *Basic engineering plasticity*. Butterworth-Heinemann.

Rochowski, A. (2001). Die compensation procedure to negate die deflection and component springback. *Journal of Materials Processing Technology*, 115, pp. 187–191.

Roll, K., Lemke, T. & Wiegand, K. (2005). Possibilities and strategies for simulation and compensation for springback in: Smith lm, pourboghrat f, yoon jw, stoughton tb (eds). *Proceedings of the 6th International Conference and Workshop on Numerical Simulation of 3D Sheet Metal Forming Processes-Verification of Simulation with Experiment, Numisheet 2005*, pp. 295–302.

Roll, K., Wiegand, K. & Hora, P. (2008a). Benchmark 2 - influence of drawbeads on the springback behavior. *Proceeding of Benchmard Study Numisheet 2008*, pp. 45–52.

Roll, K., Wiegand, K. & Hora, P. (2008b). Influence of drawbeads on the springback behaviour. In: *Numisheet 2008*.

Roll, K., Wiegand, K., Hora, P., Manopulo, N. & Clausmeyer, T. (2008c). Benchmark 2 - influence of drawbeads on the springback behavior. *Proceeding of Benchmard Study Numisheet 2008*, pp. 53–97.

Sarkar, B., Jha, B., Mukerjee, D., Jha, S. & Narasimhan, K. (2002). Thinning as a failure criterion during sheet metal forming. *Journal of Failure Analysis and Prevention*, 2, pp. 63–64, 10.1007/BF02715421.

Sever, N.K., Mete, O.H., Demiralp, Y., Choi, C. & Altan, T. (2012). Springback prediction in bending of ahss-dp 780. *Proceeding of NAMRI/SME*, 40.

Siswanto, W.A. & Omar, B. (2009). Die surface design optimization accommodating springback assisted by an automatic surface generator. *International Journal of Material Forming*, 2, pp. 797–800, 10.1007/s12289-009-0500-2.

Smith, L.M., Yang, W., Jiang, S., Zhou, Y.J., Zhou, D.J. & Du, C. (2008). A draw bead simulator for a plurality of binder angles. *Proceedings of the 7th International Conference and Workshop on Numerical Simulation of 3D Sheet Metal Forming Processes*, pp. 439–442.

Smith, M.L., Pourboghrat, F., Yoon, W.J. & Stoughton, B.T. (2005). Proceedings of the 6th international conference and workshop on numerical simulation of 3d sheet metal forming processes-verification of simulation with experiment. *Numisheet 2005 Detroit*.

Sunseri, M., Cao, J., Karafillis, A.P. & Boyce, M.C. (1996). Accommodation of springback error in channel forming using active binder force control: Numerical simulations and experiments. *Journal of Engineering Materials and Technology*, 118, pp. 426–435.

Teodosiu, C. (2005). Some basic aspect of the constitutive modelling in sheet metal forming. *Proceedings of the 8th ESAFORM conference on material forming*, 1, pp. 239–243.

Tschaetsch, H. (2005). *Metal forming practise*. Springer.

Uemori, T., Okada, T. & Yoshida, F. (1998). Simulation of springback in v-bending process by elasto-plastic finite element method with consideration of bauschinger effect. *Metals and Materials International*, 4, pp. 311–314, 10.1007/BF03187783.

Valberg, H.S. (2010). *Aplied metal forming including FEM analysis*. Cambrige University Press.

Wagoner, R.H., Gan, W., Mao, K., Price, S. & Rasouli, F. (2003). Design of sheet forming dies for springback compensation. *The sixth International ESAFORM Conference*.

Wagoner, R.H., Lim, H. & Lee, M.G. (2013). Advanced issues in springback. *International Journal of Plasticity*, 45(0), pp. 3 – 20, in Honor of Rob Wagoner.

Wang, C. (2002). An industrial outlook for springback predictability, measurement, reliability and compensation technology. *Proceedings of the 5th International Conference and Workshop on Numerical Simulation of 3D Sheet Forming Processes, NUMISHEET 2002*, pp. 597–604.

Webb, R.D. & Hardt, D.E. (1991). A transfer function description of sheet metal forming for process control. *Journal of Manufacturing Science and Engineering*, 113(1), pp. 44–52.

Weiher, J., Rietman, B., Kose, K., Ohnimus, S. & Petzoldt, M. (2004). Controlling springback with compensation strategies. *AIP Conference Proceedings*, 712(1), pp. 1011–1015.

Xu, W.L., Ma, C.H. & Feng, W.J. (2004). Sensitive factors in springback simulation for sheet metal forming. *Journal of Materials Processing Technology*, 151, pp. 217–222.

Yang, X.A. & Ruan, F. (2012). Compensation direction for die-face adjustment based on springback compensation. *Jilin Daxue Xuebao (Gongxueban)/Journal of Jilin University (Engineering and Technology Edition)*, 42(1), pp. 103–108.

Yao, H., Liu, S.D., Du, C. & Hu, Y. (2002). Techniques to improve springback prediction accuracy using dynamic explicit fea codes. *SAE Technical Paper 2002-01-0159*.

Yoshihara, S., ichi Manabe, K. & Nishimura, H. (2005). Effect of blank holder force control in deep-drawing process of magnesium alloy sheet. *Journal of Materials Processing Technology*, 170(3), pp. 579 – 585.

Zhong-qin, L., Wu-rong, W. & Guan-long, C. (2007). A new strategy to optimize variable blank holder force towards improving the forming limits of aluminum sheet metal forming. *Journal of Materials Processing Technology*, 183(23), pp. 339 – 346.